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CANMET
Canada Centre for Mineral and Energy Technology
Centre canadien de la technologie des minéraux et de l'énergie

CIRCUITRY INSTRUMENTATION AND PROCESS CONTROL

LITERATURE REVIEW

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Mineral Processing Laboratory

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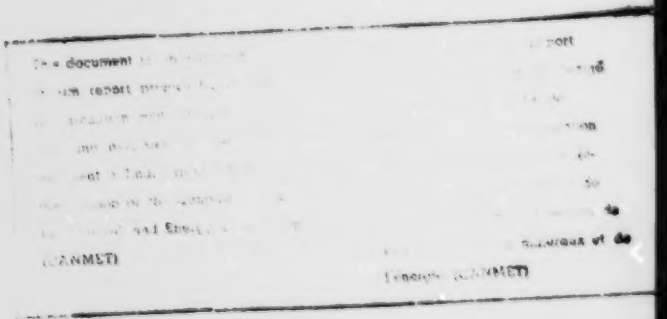
Iron Ore Processing



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INTRODUCTION

To remain competitive in the world market, Canadian iron ore producers must continually increase productivity, improve product quality and lower production costs.

Since 1982, several technical and economic measures have been introduced in the industry with excellent results. Another improvement that could further increase the industry's competitive position would be increased instrumentation and process control.

It would appear that Canadian Iron Ore Producers, along with Iron Ore Producers in the rest of the world, have fallen behind in the automation of concentrators compared to other base metal producers, e.g., the sulphide industry.

Highly sophisticated electronic hardware and software are already available, but there seems to have been a reluctance in the past by Iron Ore Producers to implement this technology. It is now time to take a close look at this area of processing, if Canadian Producers are to remain or gain a competitive edge on other countries.

CANMET, through the "Iron Ore Task Force Committee", was made aware by the industry that there is a need to assess the usefulness, on a pilot plant scale, of recent developments in instrumentation and process control, and their applicability to the iron ore industry.

It was therefore proposed that CANMET's Ore Dressing Section initiate a proposal whereby a cooperative program involving industry, equipment manufacturers/suppliers and CANMET be undertaken, at CANMET's pilot plant, to explore the above.

This kind of industry driven research, based on close cooperation and cost sharing, lies within CANMET's new mandate, and an initial proposal has been made.

This literature review was written to inform producers and CANMET of the state-of-the-art in the area of process control and instrumentation and will hopefully contribute some helpful information to the contemplated cooperative research project. It will be updated yearly in order that users may keep abreast of the most recent developments.

Keywords: Mineral processing process control, process control in concentrators, automation of concentrators, concentrator's circuitry automation, mineral processing circuitry instrumentation, measuring instrumentation of concentrators, mill instrumentation.

Explanatory Note

The Technology Information Division of CANMET, at the Author's request, carried out a search of literature on process control in mineral processing plants. They produced 580 references, being a part of the ready available Mineral Processing Databank (MINPROC). Copies of 46 articles and books from this file and about 15 from other sources have been identified as pertinent to this work and are therefore analysed and briefly commented on in the following pages.

This review also contains references and brief comments on 9 further articles of great interest which were kindly provided by Control International Inc.

This report is divided into three main parts:

Part 1: Brief description of the present state of art.
Part 2: Tables (in support of Part 1).
Part 3: References; Abstracts and comments, divided into four sections:

0. Selection of Most Pertinent Publications
1. General
2. Iron Ore Concentrators
3. Particular Circuits

INTRODUCTION

Pour demeurer concurrentiels sur le marché mondial, les producteurs canadiens de minerai de fer doivent sans cesse accroitre leur productivité, améliorer la qualité de leurs produits et abaisser leurs coûts de production.

Depuis 1982, plusieurs mesures de nature technique et économique prises dans l'inductrie ont donné d'excellents résultats. Un autre moyen d'améliorer la position concurrentielle de l'industrie serait de mettre l'accent sur l'instrumentation et la régulation des procédés.

Il appert que les producteurs canadiens de minerai de fer, tout comme ceux des autres pays, n'auraient pas autant automatisé leurs concentrateurs que d'autres producteurs de métaux de base, tels que les producteurs de sulfures.

Il existe déjà sur le marché des matériels et des logiciels électroniques très sophistiqués, mais les producteurs ne semblent pas avoir été, dans le passé, très enclins à adopter cette techonologie. Il est maintenant temps pour les producteurs canadiens de s'intéresser à ce domaine du traitement s'ils souhaitent demeurer concurrentiels ou le devenir davantage par rapport aux autres pays.

CANMET, par l'intermédiaire du "Comité du groupe de travail sur le minerai de fer", a été mis au fait par l'industrie de la nécessité; d'évaluer l'utilité, à une échelle-pilote, des progrès récents accomplis dans les domaines de l'instrumentation et de la régulation des procédés et de la possibilité de les appliquer à l'industrie du minerai de fer.

Une proposition a donc été faite pour que la Section de la préparation des minerais de CANMET prépare une proposition pour la mise en oeuvre à l'usine-pilote de CANMET d'un programme de collaboration entre CANMET, l'industrie et des fabricants et des fournisseurs d'équipements pour analyser cette question.

Comme ce type de recherche réalisée par l'industrie se fonde sur une étroite collaboration et un partage des coûts tel que prévu dans le nouveau mandat de CANMET, une proposition initiale a été faite.

Le présent document vise à informer les producteurs et CANMET des progrès récents accomplis dans les domaines de l'instrumentaion et de la régulation des procédés et il devrait contribuer à fournir des renseignements utiles au projet de recherche conjointe envisagé. Il sera mis à jour annuellement afin de tenir les usagers au courant des nouvelles technologies.

Termes-clés : régulation des procédés dans le traitement des minéraux, régulation des procédés dans les concentrateurs, automatisation des concentrateurs, automatisation des circuits de concentrateurs, instrumentation des circuits de traitement des minéraux, intrumentation de mesure pour concentrateurs, instrumentation des usines.

Note explicative

La Division de l'information technologique de CANMET, à la demande de l'auteur, a réalisé une recherche documentaire dans le domaine de la régulation des procédés dans les usines de traitement des minéraux. Elle a produit 580 notices bibliographiques qui font partie de la base de données sur le traitement des minéraux (MINPROC). Des copies de 46 articles et d'ouvrages répertoriés dans ce fichier et dans environ 15 autres sources sont considéréés pertinentes à ces travaux Ils sont, par conséquent, analysés et brièvement commentés dans les pages suivantes.

Cette analyse contient également des renvois et de brefs commentaires sur neuf autres articles très intéressants, généreusement fournis par Control International Inc.

Le présent rapport est divisé en trois parties principales :

Partie 1 : Brève description de l'état actuel de la technologie
Partie 2 : Tableaux (appuyant la partie 1)
Partie 3 : Bibliographie; Résumés et remarques, divisés en quatre sections :

0. Sélection des publications les plus pertinentes
1. Généralités
2. Concentrateurs de minerai de fer
3. Circuits particuliers

Present state of art; Comments

History

In the early seventies, automatic process control in mineral processing was a kind of hobby rather than an economically justified technical method. In the technical literature a lot of space was devoted to justifying the need for process control. The automation which started with interlock systems developed into distributed, stabilizing control techniques based on analog systems.

In the late seventies, process control, still based mainly on analog controllers, developed to central computer multi-variable systems. Since then digital controllers and model based integrated systems have been developed. Artificial intelligence systems, based on integrating a number of expert systems, are being introduced now. This last technique is still in its infancy.

The historical development has been time limited by slow advances in producing reliable hardware and adequate software, namely process sensors, measuring instruments, distributed control systems, controllers, accurate process models, easy to use plant simulators.

The attitude of people has changed with this progress. A lot has been said about psychological factors, governing the acceptance of process control by the staff of existing plants. While a certain resistance must be overcome, after a few months it stops creating major problems.

Basic definitions (After J.A. Herbst, W.T. Pate, F. Alba, L.B. Hales, B. Burdett.)

"The heart of a total plant integrated control is an economic objective function that continuously monitors all of the process factors that affect plant profitability. The impact of every control decision in each plant area is reviewed to access its impact on the total profitability of the operation.

On line real time processing information is continually available to plant personnel to aid them in their decisions as well as recommend plant changes that improve plant profitability. Even scheduling of maintenance shut-down and of batch operations may be planned according to the system improving the plant profitability.

To accomplish all this, advanced on-line plant simulators are used. They are based on accurate process models and combine the simulation results with historical data in an "Expert System Decision Strategy". They are continually looking at the impact that each decision has on the plant profit equation".

Such systems have been successfully introduced in many sulphide ore flotation plants, integrating mainly grinding and flotation, but often auxiliary operations as well.

Not all plants are introducing such complete advanced systems. Many of them are installing modern process control systems only for particular sections of the plant, leaving other sections to less ambitious manual control or simple analog or digital Proportional Integral Systems.

Modern Distributed Control Systems are basically individual control loops. They are typically implemented by feedback control loops, where one process variable is manipulated to maintain another at a selected set point. Proportional Integral Derivative (PID) controllers are routinely used for this function. Such systems also greatly improve the profitability of plants and mines.

There are many reasons for using still such less modern systems but one of the most important is that the development of adequate measuring instruments is still behind the electronics.

Economy

The ultimate goal of a contemporary integrated total process control system is the optimization of the economic effectiveness (profitability) of production. In many recent publications, authors claim that the process

control of mineral processing plants is highly profitable. The pay-off period ranges from a few months to two years at most.

Designing process control

Typical, generally accepted systems of process control of mineral processing plants do not exist. In each case the most adequate system must be designed "from scratch".

There are only a few companies which have the skills and experience to:

- Quantify the benefits of a total plant control system.
- Turn the interest into a functioning system that would meet the original design criteria.

Table 1 shows a few companies capable of designing modern mineral processing plant process control systems.

Iron ore concentrators

Total integrated process control is most developed at sulphide ore flotation plants. Iron ore concentrators are less advanced for the following reasons:

- Before 1982 the iron ore market was taking "everything" regardless of the quality of products. No particular care in processing was necessary.
- Iron ore processing is relatively new. Formerly, only rich ores that did not require processing were exploited. Therefore there is no long tradition of sophisticated technology.
- The price per ton of iron ore is much lower than of sulphides; therefore the need for great sophistication of the technology is less obvious.
- Since 1982 the difficult iron ore market situation did not permit most companies to spend large funds on research and development.
- On-stream analysers capable of analysing elements with low atomic numbers, like Si or Al, and to distinguish between Fe and Mn are developing slower than their counterparts for non-ferrous metals.

Now, after radical changes in the market situation and consequently in people's attitudes, we can expect a worldwide trend towards automation of iron ore processing plants.

In the early eighties, 2 plants with a quasi integrated process control system were reported:

- Reserve Mine (Minnesota) (modernized in 1983) where the on-stream Si analyser NOLA was first introduced.

- The Mount Newman Mining Co. Pty. Ltd. Beneficiation Plant at Newman, Western Australia, where among other things the Reichert cone concentration section was automated.

Other concentrators like Kudremukh Iron Ore Co. Ltd., India had partially integrated process control systems in 1984. General overviews of progress achieved in mineral processing in such technical magazines as Mining Engineering do not report any important break-throughs in the iron ore industry in recent years. There are, however, many distributed control systems in iron ore processing plants.

The Canadian iron ore industry must find answers to two questions:

1. What degree of automatic process control would be most beneficial at present, especially for concentrators?

2. Should the spiral section be integrated within a total system?

Instrumentation for iron ore

The particle size of ground products flowing through an iron ore concentrator is usually much coarser than in case of non-ferrous metal ores. Therefore it is difficult to use most on-stream X-ray analyzers for iron ore. This difficulty can be overcome by special handling (grinding, pulverization) of samples in near-stream by-passes, and by using, where possible, instruments capable of measuring bulk materials, like on-line belt analysers (BELTCON 100 GS-OutoKumpu; SIROSA-(SIRO); ELAN MHD-Motherwell,

(see table 2 and references, sections 0, 1.4, 3.5]. These latter are, however, less accurate than analysers measuring finely ground pulps.

The accuracy of measurement is the higher:

- the greater the atomic number of the element
- the higher the concentration of the element
- the smaller the particle size
- the higher the pulp density

Errors are caused by:

- variations in the particle size distribution
- variation in the composition and variety of mineral types
- variation in mineral grain size
- entrained air

For materials like iron ore and coal, where analysers must distinguish between Fe, Mn, Si and Al, neutron activation analysers are supposed to be more suitable than X-ray analysers.

Existing neutron activation analysers are based on a radioactive source emitting neutrons, or alpha particles exciting target elements to emit neutrons. Outokumpu says that in about a year a neutron emitting tube for analysers will be developed. Among advantages of this solution is cited the fact that unlike isotope sources which are always present in the plant, therefore theoretically dangerous, a tube emits radiation only when necessary; normally it remains switched off.

For on-stream analyses of Si in iron ore, the only instrument commercially used in Northern America is NOLA (Neutron Activation On-Line Analyser). It was first used first at Reserve Mining Co. (since 1983). By 1986 it had been installed in at least 8 operating iron ore concentrators including Sherman Mines (Ont.). Introducing this system enabled Reserve to

reduce and control its final iron ore pellet silica content from 9.0±0.77 to 5.0±0.26 per cent. Nola is produced by Texas Nuclear, Texas.

Table 2 of this report gives examples of on-stream analysers capable of measuring Fe and/or other components of iron ore (Si, Mn, Al).

The potential of On-stream Particle Size Analysers

On-stream particle size analysers (PSA) are getting more and more important for integrated total control systems.

The number of principles on which PSA are based is large but only a few true on-line, real time monitors are currently commercially available. So far, single point characterization of product size distribution is predominant, because of robustness and stability, although multi-point analysers are possible. J. Herbst and F. Alba 1986, (see references section 1.4) from the University of Utah, who co-operate closely with Control International, describe and discuss the four most successful PSA; Leeds and Northrup: Microtrac; Armco-Autometrics: PSM-400; Heath and Sherwood: PSA: Proassist Co.: SDA21 (They also mention 24 others), (see table 3).

They describe the practice of integrating an on-line size monitor into an automatic control loop. This has not become current practice yet. In the copper ore grinding circuit at Kemcott's Bonneville plant, a PSM-400 on-line analyser was used. The controlled variables are the particle size in the hydrocyclones overflow (% + 100 mesh) and the sump level. The manipulated variables are fresh ore feed and sumpwater addition.

This system is an application to an adaptive optimal control strategy technology. Estimation of unmeasured variables showed that in order for the estimator (extended Kalman filter) to uniquely identify a disturbance to the circuit, to allow proper control actions to be taken a minimum of one direct particle size measurement in the circuit was necessary. Comparison to a classical PID (on another line of the same plant) showed great advantage. Product size became more constant, the product finer, operating at a higher feed rate.

In iron ore processing the implementing of PSA would probably be most beneficial, in particular in concentrate regrinding circuits before pelletizing.

On-stream mineralogical analysis

Having an on-stream liberation determination, based on an image analyser would be certainly beneficial for rendering grinding circuits more efficient and predicting recoveries of down-stream separation circuits. No instrumentation for this purpose is available to date. W. Petruk (CANMET) estimates that a team of adequate experts could develop a fast, automatic method (lasting minutes instead of hours) of measuring the liberation of minerals in about 2 years, after the commencement of such a project.

Table 1 Companies Able to Design and Implement Modern Process Control Systems in Concentrators

	Company	Person
1.	Comdale Technologies Inc. 833 The Queensway Suite 202 Toronto, Ont. M8Z 5Z1 Fax (416) 252-9998 Tel. (416) 252-2424	C. Anthony Harris Computer Applications Engineer
2.	Control International Inc. 2319 Foothill Drive, Suite 200 Salt Lake City, Utah 84109 Tel. (801) 486-4655	Lynn B. Hales, Manager John A. Herbst, Manager
3.	Ramsey Canada 385 Enford Road Richmond Hill, Ontario L4C 3G2 Tel. (416) 883-1881 Telex 06-986722 Fax (416) 883-1730	Doug Young, Sales Manager
4.	Outokumpu Oy, Finland To inquire at Outokumpu Equipment Canada Ltd. 6495 Northam Drive Mississauga Ont. L4V 1G2 Tel. (416) 6713304; Fax (416) 671-8413	Matti Tarvainen, General Manager
5.	Humboldt-Wedag P. Box 102729, D-4630 Bochum 1 West Germany Tel. Bochum (0234) 539-682 Fax (0234) 539-218	I.A. Farahmand
6.	Boliden Boliden Contech AB Box 45118 S-10430 Stockholm Tel. 4687369800 Fax 468325995	B. Nordwall, Manager
7.	Industrial Control Subsidiary of Texas Instruments Maryland	
8.	ARMCO Autometrics 7077 Winchester Circle Boulder, Colorado 80301	

Table 2 On-stream X-ray and Nuclear Activation Analysers

Kind, Name	Production	Type	Characteristic
1	2	3	4
I Centralized systems			
Courier 300	Outokumpu Oy Finland (Outokumpu Equipment Canada Ltd. 6495 Northam drive Mississauga, Ont. L4V 1J2 Tel. (416) 671-3304	Fixed flow cells-Movable X-ray; Modular, up to 14 cells in 3 modules, X-ray Tube.	Six elements Range, above Ti (22), WDX
Monitor 1000	Harrison R. Cooper Systems USA	Fixed spectrometer unit, Movable cells, 14,28 and 42 flow cell units, X-ray Tube.	Above Ti (22) WDX
Monitor 2000	"	as above	Above Mg (12) WDX
Boxray 16 and Boxray 8	Boliden, Sweden (Boliden Canada Ltd.,) Toronto Tel. (416) 581-1561)	Fixed spectrom. Movable cells, X-ray Tube.	Above Si (14) EDX, secondary target radiation.
ASOMA Model 8660	EG & G Instruments (EG & G. Canada Ltd., Markham, Toronto Tel. (416) 475-8420	Radioactive source: Fe-55, Cm 244, Cd -109, Am, -241 or Cm 244.	Above Mg (12)
XEG X-ray	Humboldt-Wedag Post. Box 910404D Koln Phone (0221) 823-1 Western Germany	X-ray Tube	Above Mg (12) Measuring Dry sample possible.

Table 2 cont'd

Kind, Name	Production	Type	Characteristic
1	2	3	4
NOLA	Texas Nuclear, Texas (Ramsey Engineering Richmond Hill, Ont. Tel. (416) 883-1881	Radioactive Source Pu-Be α-n	Measuring Si in iron ore accuracy ± 0.2% (Slurry 20-70% solids and 5-6% Si). Special treatment of the sample that is recirculated for longer irradiation and measuring time. Nola can be within a centralized system or near-stream.

Table 2 cont'd

Kind, Name	Production	Type	Characteristic
1	2	3	4
II Distributed Systems			
a. In-stream	–	–	EDX, Low accuracy when low metal concentrations.
AMDEL	AMDEL, Australia 31 Flemington St. Glenside 5065, South Australia 08-372 2700, Telex AA82520	In stream (scintillation counter) EDX	EDX, pulp density simultaneously; low resolution.
INSCAN	Texas Nuclear (Ramsey Engineering) Richmond Hill, Ontario, Tel. (416) 883-1881	In stream Source: Pu 238 or Cd 109 or Am 241 or Cm 244 (proportional counter) EDX, Solid State detector	Above 15 (P) EDX Good resolution
Minexan -202	Outokumpu Oy Finland	In stream (and near stream) EDX Proportional counter.	5 elements and pulp density simultaneously. Low resolutions.
b. Near-stream			
1 X-ray Tube/Diffraction Crystal			Excellent sensitivity and accuracy. More costly than in-stream.
Courier 30	Outokumpu Electronics, Finland		
Monitor 500	Harrison R. Cooper Systems Bountiful, Utah Tel. (801) 295-2345		Range Si (14) and above.

Table 2 cont'd

Kind, Name	Production	Type	Characteristic
1	2	3	4
2. X-ray Tube/Solid State Detector			Good resolution and sensibility.
Boliden	Boliden Metal Aktiebolag Copper, Sweden	EDX, with secondary target	
XRA -1500	Armco Autometrics 7077 Winchester Circle Boulder, Colorado	"	
3. Radioisotope/Solid State Detector			High resolution good for distinguishing elements with close atomic numbers.
Inax	INAX, Ottawa Bondar-Clegg, Ottawa Ramsey Rec. Ltd., Richmond Hill, Ont.	Source Iodine -125	
4. Radioisotope/Proportional Counter			Not expensive but resolution low. Not good for consecutive atomic numbers.
Minexan 202	Outokumpu Oy Finland	Near-stream and In-stream	5 elements and pulp density EDX.
On line belt analysers			
Beltcon 100GS	Otokumpu Electronics Finland P.O. Box 85 SF-02201 Espoo Finland Tel. 358-04211	Source 2x Am -241 2x Cs -137	Measures the sum of metal over 0.5%. Range 20 (Ca) to 30 (Zn) Particle size 0-200 mm Temperature -30°C + 40°C

Table 2 cont'd

Kind, Name	Production	Type	Characteristic
1	2	3	4
Nucoalyzer - CONAC Continuous On-line Analyser of Coal.	Science Application International Corporation 1257 Tasman Drive Sunnyvale, CA 94089	Prompt Gamma Neutron Activation Analyser Radio Isotope Source.	Used for analysis of coal, measuring N,S,C,N,CL,Si,Al,Fe,Ca,Ti,K,Na. Range under 5% of Fe. Belt or pipe analyser. Detectibility above 0.1 wt % Up to 12 elements, with high resolution. Time of analysis 1-5 min. for S. and ash content but 30 min. for Na.
Continuous Flow-Thru Coal Analyser.	Gamma-Metrics 5550 Oberlin Drive San Diego, CA, 92121	Prompt Gamma Neutron Activation	Used for analysis of coal. Ash and sulphur content was measured. Range-under 5% of Fe. Time of analysis 1 min. Closed loop (recirculation) and open loop possible. Samples taken from the belt.
ELAN, Bulk Material On-Line Analyser.	MDH-Motherwell, Inc. 426 West Duarte Road Monrovia, California 91016	Prompt Gamma Neutron Activation, Source Cf-252	Measures free falling coal. Time of analysis 10 seconds, Analyses-among others - SiO_2, Al_2O_3, Fe_2O_3, K_2O, can be adapted to iron ore, would distinguish between Fe and Mn.

On-Line Particle Size Analysers

Table 3 Comparison of Characteristics (after J. Herbst, F. Alba)

	Leeds Northrup	Armco-Autometric	Heath Sherwood Canada	Proassist Co.
ANALYZER	MICROTRAC	PSM-400	PSA	SDE-21
NUMBER OF POINTS	Laser 13	Ultrasonic 1	Sedimentation 2 (4 optional)	Ultrasound attenuation 5
MEASUREMENT CYCLE	2-3 min.	2 sec.	6 min.	25 sec.
ACCURACY AND PRECISION	±2%	±2%	±3%	±2%
SIZE OF SAMPLE	small	large	medium	large
SAMPLING SUBSYSTEM	complex	simple	medium	simple
NEEDS DILUTION	yes	no	yes	no
MEASURES CONCENTRATION	no	±3%	no	±1.5%
WET/DRY	wet & dry	wet	wet	wet
ROBUSTNESS	medium	high	medium	high
MAINTENANCE	medium	low	low	low
OPERATOR INTERFACE	good	good	good	very good
COST/U.S. $	50-60k	50-60k	24k	(needs PSM-400 electronics), 15k
Installed currently	over 50	350	?	?

Section O. Selection of most informative, recent and/or pertinent articles

O. C.A. Harris
G.A. Kosick

Expert System Technology at the Polaris Mine, Canadian Mineral Processors Annual Operators Conference, Ottawa, January 1988.

This paper describes the procedures followed in constructing "the first" (according to authors) process controller in the mineral industry which is based on the principles of Artificial Intelligence. The introduced system should embody and utilize heuristic "rules-of-thumb" gained from operators to make on-line process decisions. It would also justify these decisions on a demand basis.

The existing, already highly automated plant is described. The new system and its introduction using COMDALE/C technology is depicted. This article is a useful introduction to somebody wanting to become familiar with Expert Systems.

C. D. Laguitton

Expert Systems in Mineral Processing, CANMET, Division Report MSL 88-6(OP&J) Jan. 88.

This paper can be treated as a kind of manual of Artificial Intelligence (AI) and its application in mineral processing.

It reviews technical and human considerations in expert system prototyping and "should assist mineral processors in planning their first steps in AI applications".

It is an attempt to define the basic glossary of expert systems, illustrate the power and limitations of this technology, outline a strategy for the first time user and present actual case-stories of CANMET-sponsored applications.

O. S.K. Kawatra, Harrison R. Cooper

On-Stream Composition Analysis of Mineral Slurries.

Design and Installation of Concentration and Dewatering Circuits, Editors: A.L. Mular, M.A. Anderson. Publ. Society of Mining Engineers Inc., Littleton, Colorado, 1986.

The article presents a review of on-stream analysers explaining principles of their functioning, indicating advantages of selected types for particular purposes and mentioning examples of their application.

0. J.A. Herbst, W.T. Pate, F. Alba, J.L.B. Hales, B. Burdett

Development of an Adaptive Optimal Control Strategy for an Industrial Rod/Ball Mill Grinding Circuit.

The article explains using a rod/ball mill grinding circuit as an example, the superiority of an optimal control strategy over conventional proportional-integral control, self tuning regulators and decoupling control.

The optimal control theory requires a model of the process that describes its dynamic behaviour and a performance index to be minimized. For specific forms of the model and performance index the minimization process results in a feed back optimal control law that, unlike conventional P.I. control, is multivariable. That is, the manipulated variables are determined simultaneously from an optimal combination of process variables in the circuit. The variables of the described circuit that can be adjusted are rod mill ore feed rate, rod mill water addition and the sump water addition rate. The cyclone feed pumps are fixed speed.

O. B.W. Burdett, L.B. Hales, T.I. Probert

Selection of Control System for Concentrator Operations.

"Design and Installation of Concentration and Dewatering Circuits"; Editors: A.L. Mular, M.A. Andrews; Society of Mining Engineers, Inc.; Littleton, 1986.

This article approaches problems of process control from the designer point of view. Advantages and disadvantages of different equipment types, configurations and control strategies are described. Selection procedures are detailed and the importance of each step in the design and selection process is explained.

O. Ralph J. Holmes

On-Stream and Bulk Analysis of Iron Ores.

Bulletin and Proceedings of the Australian Institute of Metallurgy Vol. 290, No. 1, Feb. 1985.

The Commonwealth Scientific and Industrial Research Organization (CSIRO) Division of Mineral Physics has developed a number of bulk analysis techniques in which analyses are obtained directly from ore samples weighing many kilograms or from ore located on conveyor belts. Because penetrating neutron and gamma radiation is used, measurements are obtained from a large volume of ore, which ensures that the analyses are representative of the bulk.

Two different gamma-ray techniques have been developed to measure iron ore grade. The first is based on back scattering of ^{60} Co gamma-rays while the second involves measurement of the annihilation radiation which arises when the ore is irradiated with ^{226} Ra gamma-rays. Both techniques measure the iron concentration with an accuracy (1 σ) of better than 0.4% Fe.

A thermal-neutron irradiation technique using a ^{252} Cf neutron source has been developed for the simultaneous determination of iron and the aluminium impurity (expressed as Al_2O_3) in iron ore fines on a conveyor belt. Because the conveyor speed must not exceed about 0.05 m/s, if good accuracy for Al_2O_3 is required, an auxiliary analysis belt is required to avoid interference with normal ore processing. Dynamic trials have demonstrated that accuracies of 0.6% Fe and 0.1% Al_2O_3 can be obtained.

Ores for which CSIRO work has been done must be different from Canadian ores, since Al_2O_3 was measured rather than SiO_2. However, to measure Si (atomic number 14) using nuclear techniques is usually easier than Al (a.n. 13); therefore the described techniques might be useful for Canada.

O. J.A. Herbst, L.B. Hales, W.T. Pate

Documentation of Improvements Resulting from the Automation of Mineral Processing Operations.

Report of Control International Inc., Salt Lake City, Utah 1987.

Prior to installation of a control system the strategy to be used has to be determined and the expected improvements in process performance evaluated. In order to obtain an accurate assessment of improvements, statistical methods can be employed. This paper describes the development of a methodology for making these evaluations. The basis for evaluation and comparison is some freely chosen measure of process performance called the performance index-"an objective function". Alternative strategies may be compared by the performance index on either a technical or an economic basis. Examples of using the "performance index" are shown for a rod/ball mill circuit, flotation circuits. The developed methods can serve not only for predicting results but also for evaluation of existing circuits.

O. C.A. Harris, J.A. Meech

Fuzzy Logic: A Potential Control Technique for Mineral Processing.

C.I.M. Bulletin Sept. 1987

Authors develop the idea of replacing strict mathematical models of mineral processing, as used for process control, by "fuzzy" models. They claim the possibility of practical implementation of their theory in a secondary crushing plant.

Mineral processes typically are characterized by non-linear relationships between input and output variables. Many of these variables cannot be monitored accurately (e.g., ore characteristics) on-stream and long time lags on the measurement loops are features of the system. Mathematical models describing each unit activity are mathematically rigorous and their complexity and precision limit their usefulness when applied to "vague" processes.

The strategy using the theory of Fuzzy Logic is based on the actual plant practices of experienced operating personnel.

This paper illustrates the concepts pertaining to the design implementation and operation of a Fuzzy Logic controller in the context of a secondary crushing plant.

0. J.A. Herbst, L.B. Hales, R. Zaragoza
Strategies for the Control of Flotation Plants.

Report of: Dept. of Metallurgy and Metallurgical Engineering, U. of Utah, Salt Lake City; Kennecott Copper Corporation, Salt Lake City 1987.

This paper gives the description of the hardware and control strategies which can be used to improve flotation plant performance. The direct result of the application of classical control methods provides gains in process efficiency (increase of recovery and reduction of reagent consumption). An advanced model-based multivariable control system is a better way. It also minimizes instrumentation needs, and therefore capital costs, for control system implementation. The list of references includes 64 items dating from 1965 to 1986.

0. J.A. Herbst, F. Alba, Jr.

An Overview of On-Line Size Measurement Devices Which are Suitable for the Control of Particulate Production Processes.

Paper of the University of Utah, Generic Mineral Technology (Center in Comminution, Salt Lake City, Utah 84122), 1986.

This paper discusses the characteristics of on-line size measurement devices which make them useful for automatic control. The importance of such characteristics as measurement accuracy, sampling frequency, precision, percent availability, number of points on the size distribution measured, ease of calibration and cost are examined. Commercially available devices which are suitable for control are reviewed. The paper concludes with two case studies involving the use of sonic attenuation-based instruments. These case studies clearly illustrate the benefits of on-line size measurements for the control of particle production processes. A very good article with a list of 41 related articles dating from 1972-1986.

0. B.A. Wills

Automatic Control in Mineral Processing

Mining Magazine April 1987

This article introduces the concepts and terminology and reviews the practice of process control in mineral processing. It can serve as a simple yet adequate introduction to Automatic Control in Mineral Processing for technologists with little expertise in automation.

Section 1. General

1.1 Introduction to process control
1.2 Examples
1.3 Selection of systems, control strategy
1.4 Circuitry instrumentation
1.5 Economics

1.1 E.G. Kelly, D.J. Spottiswood

"Introduction to mineral processing"; New York, Wiley-Interscience; 1982

Chapter "Plant Control" gives a brief and clear introduction to process control of mineral processing plants. It describes control objectives, principles of automatic process control (control systems, analyses of process dynamics, controllers and control algorithms, stability of control systems, modern control concepts, instrumentation). It discusses selected control applications (crushing, grinding circuits and flotation control). The list of references includes 44 items dating from late sixties to 1980. Systems based on artificial intelligence are not considered.

1.1 D.G. Hulbert, I.J. Barker

The Control and Optimizing of the Operation of Milling Circuits.

Proceedings of MINTEK50, Sandton, March 1984.
Published by The Council for Mineral Technology, Randburg, South Africa.

Fundamental aspects of the control of wet milling are discussed. Particular reference is made to an industrial application of multivariable control in which the size of the product is controlled and two other set points are selected according to a practical scheme that results in the maximum throughput at the required size.

"Grinding is an operation for which there is not yet a generally accepted method of control for the achievement of optimum results, however it is now generally recognized that grinding is an inter-active dynamic process that requires some form of multivariable control for its efficient operation".

"A great deal of what happens in a grinding circuit is not measurable. This makes the control of a circuit difficult and dependent on metallurgical knowledge and modelling techniques."

An example of a milling circuit at East Driefontein is described.

1.1/1.2 M. Garon

On Line Computer Applications in Mineral Processing.

Proceedings, CIM, 86th Annual Meeting; 1984.

Computer control of the flotation process was successfully implemented in the Mattagami Concentrator of Noranda Mines in 1974. Recently selected areas like the copper and zinc concentrate dewatering and the lime preparation system were provided with programmable or independent analog controllers. Also control of frother addition in the final copper cleaners has been transferred from the computer to an independent analog controller.

Types of controllers:

1) Fisher and Porter, Scan Line, type 53EG and 53MC (analog, PID based)
2) Modicon Micro 84 from Gould, (2k memory, 16 input/output)
3) Allen Bradley controller

Other equipment: ARL On-stream X-ray analyser
PDP8M-DS computer from Digital Equipment

1.1/1.2 J. Miettunen

The Pyhasalmi Concentrator - 13 Years of Computer Control.

Proceedings: Automation in Mining, Mineral and Metal Processing; IFAC Symposium, Helsinki, Aug. 1983; Published by Pergamon Press, Toronto.

The paper describes the main stages of development work on process control at the Pyhasalmi concentrator until it reached the present state of "economic control". Economic control means that the goal is no longer to produce concentrates of constant quality but to maximize the net cash flow of the whole mine.

The control systems of grinding and flotation are also described. The control systems of both Cu and Zn flotation comprise fast stabilizing control and slow, adaptive optimizing control. Benefits of computer control are described.

1.2 A. Trusiak

Computer Control of Brunswick Mining's No. 12 Cu - Pb Flotation Circuit.

Proceedings: Thirteenth Annual Meeting of the Canadian Mineral Processors, CANMET, January 1981.

An example of process control introduced to the polymetallic sulphide ore (Cu,Zn,Pb,Ag) flotation plant is described. Assaying is performed by an on-stream 28 Stream Courier 300 X-ray analyser. As control system, the Proscon 103/105 has been chosen for flotation only, keeping in mind future expansion to the grinding, crushing and dewatering processes. The Proscon 103 consists of a centrally located operator's console, a digital-to-analog conversion interface and a DEC PDP 11/34 computer with 32k memory. Control actions are performed using a PID algorithm. The Proscon 105 is used in a data-logging role. The system consists of a DEC PDP 11/34 computer with 64k of core memory, two video terminals, one low speed printer and two high-speed printers for report generation. Data is transferred from the Proscon 103 to Proscon 105 every six minutes. The control strategy is briefly described. Metallurgical results before and after installation of the control system are summarized.

1.2 J.L. Bolles, A.J. Broderick, H.R. Wampler

"Morenci Concentrator process control system"; AIME Transactions Vol. 262, Dec. 1977.

A process control system controlling 30 primary grinding circuits and all reagent additions of a copper ore concentrator is described. It consists of a centralized control room, process control computer, on stream X-ray analyser, on stream particle size analysers and an operator interface. The paper describes the process control system development, control concepts and its influence on the concentrator performance.

Centralization of control to a process control centre simplifies computer applications. Three Process Control Systems are distinguished: 1. electronic and pneumatic controls located in the immediate area of the machines or process; 2. centralized analog control; 3. centralized computer control.

The primary objective of process control introduction was increasing copper production. The particle size control algorithm was designed on the basis of experimental analysis. It was assumed that it was desirable to grind finer when the copper in the mill feed increased (maximizing recovery at the expense of maximum throughput) and to grind coarser when the copper in the mill feed decreased (maximizing throughput at the expense of maximum recovery).

The collector control system is based on a linear equation relating % Cu in the concentrate and % Cu in the final tailing to collector addition.

Economic benefits of process control ore analysed, benefits shown.

1.2 L. Chutshoff, K.C. Carrière, L. Betteridge, B. Dishaw

"The implementation of process computer control at the Snow Lake Concentrator".

Proceedings: 3rd IFAC Symposium, Montreal, Aug. 1980; Pergamon Press, Toronto.

Introduction of a computer system to control flotation of multi-metallic sulphide ore is described. On-stream ARL XRF analyser provides operator data. Computer supervisory set point (SSP) control rather than direct digital control (DDC) was selected because of its simplicity. It was decided to use the computer to enhance conventional analog control without placing undue reliance on computer availability. Criteria for the computer selection are laid out. The system configuration, possibilities of real-time fortran extentions and application programs are discussed. Both system hardware and application programs were modular allowing easy implementation at another site.

1.2 T. Merituoto

"Automated concentrators of Outokumpu".
World Mining; May 1983.

A brief review of the history and achievements of process control developed at the world-wide known polymetallic sulphide ore concentrators at Outokumpu, Finland is given. Lists of Finnish and non-Finnish Outokumpu Concentrator Automation systems are presented. Elements of the process control plans of the following concentrators with digital control systems are described: Pyhasalmi, Vuonos Kotalahti, Keretti and Vihanti.

1.2/1.3 L. White

Pyhasalmi Concentrator Stays One Step Ahead of the Field, "Engineering and Mining Journal", April 1984.

This article, based on information supplied by Outokumpu staff, describes the Pyhasalmi mine and concentrator, strategy and equipment for concentrator process control, hardware configuration and control principle. Copper flotation control is based on the economic recovery. What makes the strategy one step more advanced than in most automatized concentrators in the world is optimizing technological rather than economic results. The use of Courier 300 X-ray fluorescence on-stream analyser and the new Otokumpu Proscon 20/200 computer system is described.

1.2/1.3 K. Koichiro, K. Tyama

Recent Development in Computer Control Using On-Stream XRF Analyser for "Kuroko" Flotation Process of Dowa Mining Co., Ltd.

First Intnl. SME-AIME Fall Meeting, Honolulu, September 1982.

The grade of the feed to the concentrator averages 0.9 g/t Au, 110 g/t Ag, 1.1% Cu, 2.8% Pb, 9.2% Zn, 5.0% Pyrite-S and 13% $BaSO_4$. The recently introduced automatic reagent control system consists of On-Stream X-ray Fluorescence Analyser (OSA), Central Processing Unit (CPU), Cathod Ray Tube (CRT) and Control Units. This system calculates every 10 minutes the material balances and flotation rate constants in the circuit based on the OSA assay data, and then predicts the assay of flotation products. According to the prediction, reagent additions at five points are automatically controlled. Installation of the control system has made stable operation by only two operators in the grinding and flotation sections possible, brought about reduced collector consumption and improvement of recovery of metals. It increased the plant capacity by about 10 percent. The article shows the arithmetic of balance and assays calculation.

1.3 1.4 3.8 R.Y. Allee, L.B. Hales

Cleaner Flotation Control at Chino Mines Company.
Report of Control International Inc. and Chino Mines, SME Fall Meeting, St. Louis, Mo, 1986.

Automation of a molybdenum-copper ore concentrator is described.

Circuitry instrumentation includes a TDC-2000 distributed control system, a Honeywell 4500 computer and Hewlet-Packard Micro 29, interfaced with the latter one, and an Outokumpu Courier 300 on stream X-ray analysis system. The control program has been successful in increasing cleaner recovery by 0.32 percentage points. Work on rougher flotation control was under way at that time.

1.3/1.4 V. Cosgriff

Retrofitting Process Controls to the Climax Mill, Engineering and Mining Journal, May 1982.

At the Climax Molybdenum concentrator, a program for installation of process controls was started in 1970; however only in the past few years has the system produced the results desired, after a software package was developed that was readily understood and accepted by mill operating personnel. The article shows how earlier mistakes could be avoided. It discusses in detail problems resulting from the wrong control strategy and inadequate selection of equipment and indicates how these problems were overcome. The evolution of the control system is described. The system (hardware and software) and most auxiliary equipment was supplied by Foxboro.

1.3 ...

Computers; Milling Control Instrumentation is no Luxury - it's Essential.

Coal, Gold and Base Minerals, July 1983.

A proposal for automation of East Driefontein Gold Mine's grinding circuit is described in a very simple manner. The research work preceeding the establishment of a proposal started with a computer simulation of the plant. Selection of variables, plant tests with the aim of altering the simulated model to achieve the real dynamic characteristics of the plant and finally feedback and feed forward controller design were carried out. A multivariable system was chosen for application to the plant. As a result, the plant could be controlled at different operating points while still producing material at the same flowrate and at the same measured size. Mintek designed two dedicated microprocesser-based systems and installed them in the plant - one for the implementation of the control strategy, the other for data-logging. The multivariable control scheme does not contain a procedure for automatic optimization of the circuit but deals with the dynamics of the process and maintains the operation at set points that can be chosen according to an external scheme of optimization. Prerequisites for this scheme are described.

1.3 G. Sommer, A.B. Stewart

The Introduction of Advanced Control Equipment into Mineral processing Operations.
Proceedings: 4th IFAC Symposium, Helsinki, August 1983, Edited by T. Westerlund, Pergamon Press, Toronto

Development of advanced control strategies on mini-computer systems for mineral processing operations as well as the subsequent implementation of the adopted strategy into dedicated microcomputer-based controllers is described.

The micro-computer-based controllers are used in the multivariable control of milling circuits in gold-extraction operations.

New types of process controllers, more "intelligent" and more "devoted" to the problems encountered in mineral-processing operations, have been developed. Advanced control has been implemented with low maintenance requirements and without the need of a computer specialist on the plant.

1.3 C. Bazin, D. Hoduin

The Application of Time Series Analysis to Mineral Processing. Proceedings: 87th Annual General Meeting of CIM, Vancouver, April 1985.

In mineral processing plants, sensors are available to monitor pulp density, flowrate, pH, temperature, level, metal content and particle size distribution. These measurements, taken at constant sampling intervals, provide signals that can be processed by time series analysis techniques. These time series, available in many plants, should be processed to obtain all pertinent information on circuit and equipment operation.

The paper describes: 1. the basic theory for time and frequency domain analysis of time series; 2. signals used to illustrate the applicability of time series analysis to mineral processing; 3. a discussion of the results of the analysis; 4. an illustration of the application to process diagnosis and control.

1.4 T. Gorani, D.R. Brown, H. Bernatowicz, H. Bozongmanesh

The Nucoalyzer, An On-line Nuclear Analyser for Coals and Minerals.

Proceedings: 12th CMMI Congress, H.W. Glen (editor), Johannesburg. S. Afr. Inst. Min. Metall, 1982.

During the past six years, on-line nuclear analysers of coal have been developed and are now available commercially. These instruments, called nucoalyzers, represent a major advance in the real-time bulk analysis of aggregate minerals such as coal, iron and base-metal ores, and base minerals (e.g., phosphates and cement). On-line analysis, based on neutron-capture gamma-ray spectroscopy, is done non-intrusively without the need for sampling or sample preparation. This analysis of coal composition, ash content, and calorific value permits process control at the mine and beneficiation control at the preparation plant, and provides the power-plant operator with current information on the coal (e.g., fouling and slagging indices) prior to combustion, so that remedial action can be taken whenever necessary. The system ensures accurate blending so that the coal complies with the requirements for sulphur, constant ash, BTU, or any other desirable property. It also enables the producer to maximize his product while maintaining its quality.

During the 1981-1982 period, three Nucoalyzer systems were put into operation, the first at a major U.S. utility for the on-line control of the blending of high- and low-sulphur coal, effecting major savings while complying with the requirements for sulphur emissions.

The precision of the measurements for sulphur, hydrogen, chlorine, iron, silicon, and calcium (up to 12 elements), total ash, moisture, and calorific values are normally comparable with or higher than that achieved by ASTM analytical and sampling techniques.

Nucoalyzers are flexible enough to be incorporated and integrated into plants and mines without the need for major redesign or construction efforts. The Nucoalyzer system interrogates bulk materials, e.g., material 20 to 30 cm thick, regardless of particle-size distribution.

The theory of the Nucoalyzer and its application in practice are reviewed by reference to existing installations.

1.4 Harrison R. Cooper - Editor

Instrumentation in the Mining and Metallurgy Industries, Volume 12.

Proceedings of the 13th Annual Mining and Metallurgy Industries Symposium and Exhibit. May 15-17 1985 Salt Lake City, Utah.
Published by the Instrument Society of America Research Triangle Park, North Carolina.

This volume contains 22 articles on instrumentation. The most related to this project are the following:

1. A new system for on-line measurement of multi-point size distributions and solids concentrations (J.A.Herbst, F. Alba).

2. Programmable controllers make short work of process control systems (G. Riley).

3. Self-tuning control of a ball mill grinding circuit (K. Rajamani).

4. Dynamic simulation for estimation of industrial grinding circuit control characteristics (O.A. Bascur, E.J. Freeh, R.Y. Allee).

5. CMC concentrator control system (B.W. Burdett, D.L. Dison).

1.4 H. Brown, F. Riffel

A Nuclear Technique for Monitoring Silica in Iron Ore Slurries.

J. Radioanal Chem. 72(1982).

The principles of functioning and application of SUSAC - a German equivalent of the NOLA on-stream analyser is described. SUSAC was originally developed for the on-stream analysis of fluorspar.

1.4 K.L. Sandvik

Limitations to Advanced Process Control in Sulphide Flotation Plants.

Flotation of Sulphide Minerals, edited by K.S.E. Forssberg, Elsevier, New York, 1985.

Mineral processing still is in a development phase when it comes to instrumentation. This contrasts to control strategy which is fairly well advanced. There is still more to be achieved by better instrumentation and control. The principles of the multivariable optimal control of Tverrfiellet are described. The problem of availability (operational time) of different control equipment is estimated. The maximum time the process can run on this type of control is calculated to be only 50-60% of plant operational time.

Among the most common circuitry instruments, pulp flowmeters have the lowest availability (85%). The most reliable are computers.

At Tverrfiellet the copper rougher flotation is controlled. The purpose is to optimize the collector and air supply in order to establish the desired concentrate and tailings grade.

The strategy described here consists of finding a part of the flotation circuit that is crucial for copper flotation and optimizing it. The rest of the circuit to a large extent then regulates itself.

1.4 R.J. Holmes, M. Borsaru, A.W. Wylie

A Neutron Irradiation Method Suitable for On-stream Analysis of Iron Ore.

The Australian I.M.M. Conference, North Queensland, 1987.

Principles and problems of neutron activated on-stream analysis of crushed dry material are discussed. For analysers based on thermal neutron capture and activation, the belt conveyor must have relatively low speed (an auxiliary "side" belt might be required), the belt cannot be made of any chlorine-containing polymer and the ore cannot be high in Mn. The article discusses analyzing Al_2O_3 but not SiO_2.

1.4 D.B. Leech, M.A. Patterson

An Overview of Instrumentation and Controls in Canadian Potash Plants.

Instrumentation in the Mining and Metallurgy Industries, Vol. 11.
Instrument Society of America, Vancouver B.C., May 1984.

The first part of the article briefly describes instrumentation and control equipment generally utilized in potash mills prior to the 1980's (basically 1960's vintage). The second part gives an overview of current instrumentation and controls. New instrumentation introduced to both systems (Distributed Control and Programmable Control) is compared to old process sensors and other control elements. On-Stream Gamma-Ray Analysis, based on the detection and measurement of the radioactive isotope K^{40} contained in naturally occurring potassium, is the basis for a central system of control. The action, accuracy and reliability of on-stream gamma-ray analysers is presented and compared to X-ray analyser systems.

1.4 R.H. Goodman

A Slime Level Indicator.

Dept. of Mines and Technical Surveys, Mines Branch Technical Bulletin TB57. October 1964.

This report describes a very simple level indicator designed for settling tanks, based on the optical opacity of the slime compared to the liquor.

1.4 ...

How Littlewood Regulator Automatically Optimizes Ball Mill Grinding Rates.
World Mining, December 1969.

The control apparatus follows the load characteristics of the ball mill motor to determine the direction and rate of power change. It selects the optimum operating point and makes ore feed and water connection to keep the equipment operating at that load.

1.4 J. Leung

The Software of INAX X-Ray Fluorescence On-Stream Analyser.

CANMET, Division Report MRP/MSL 81-12(TR), 1981.

The author modified programs supplied by INAX Instrument Co. for better presentation of the analysis results, more freedom for the output formats, smoother calibration curve fitting and easier accessibility in changing the parameters. The report provides information concerning the capabilities of the INAX XRF on-stream analytical program and instructions for its use.

1.4 R.O. French, R.W. Vaughn, A.P. Langheinrich, J.F. Baum

Application of Continuous XRF Analysis to Mill Control.

Continuous Processing and Process Control, Philadelphia, Penn., Dec. 1966, Metallurgical Society Conferences Vol. 45 Gordon and Breach, New York, London, Paris.

The article refers to R & D work done at the time on-stream XRF analysis was being introduced for mill control. Trend studies, variance analysis, regression analysis and the development of semi-theoretical mathematical models suitable for digital computers are briefly described. For this work, data were accumulated with two different flow cells and two sampling systems. Results were reported for lead, zinc and copper milling streams.

1.4/1.5 W.E. Herst, R.C. Enochs

Instrumentation and Process Control.

E & M.J. Book of Flowsheets: P.C. Merritt, Editor McGraw-Hill Inc., New York, 1984.

Implementation of instrumentation and process control systems in old plants having multiple parallel circuits of smaller capacity is usually more costly than in new plants equipped with fewer high-capacity circuits. Nevertheless many successful installations may be cited.

This article discusses the status of current instrumentation and process control technology as applied to major unit operations in the mineral industry including crushing, grinding, classification, flotation, thickening, filtration and drying. Flowsheets for typical instrumentation schemes are included. Users, manufacturers and suppliers of instrumentation are cited.

A table showing benefits of process control implementation in particular plants is given.

1.5 G.A. Duckworth, J. Kruttschnitt

Optimal Control of Mineral Grinding Circuits: Some Problems and Practical Limitations.
CIM, 21st Conference of Metallurgists - 1982, Toronto

"It has been estimated that effective application of automatic control to comminution circuits alone could be expected to save ten percent of the energy currently consumed". "In addition to energy saving, increases in plant throughput of the order of 2-10 per cent together with increases in the recovery of valuables of the order of 1-2 per cent have been cited".

"Regulation involves holding a process variable as closely as possible to some predetermined level. Optimization involves setting the levels for regulation in such a way that the process always operates at maximum efficiency. A process cannot be optimized if it cannot be regulated."

This article discusses the relation of process regulation to optimization and presents advantages and disadvantages of different kinds of optimization. Special attention is paid to different aspects of the economic optimization and selection of correct control objectives. Primary autogeneous and semi-autogeneous circuits are considered.

Economic optimal operation of a mineral concentrator cannot be achieved by considering the grinding circuit alone. However mill throughput and product size have a major impact on the performance of on-stream operations and determine the extent to which liberation of valuable minerals occurs.

1.5 U. Paakkinen

Economics of Computer Control Applications in the Outokumpu Company.

Proceedings: The second IFAC Symposium: Automation in Mining Mineral and Metal Processing, Johannesburg, Pergamon, Toronto 1976.

The control criteria of three different processes are compared, namely mine ventilation, flotation and flash smelting. Essential characteristics of each process are described from the point of view of process control, and also the control loops and the control strategy are presented. The main emphasis is put on the economic evaluation of automation. Costs from investments, development and maintenance are compared to the benefit gained as measured with money flow. The economic recovery with computer control was nearly 2% better than with manual control. Ratio of annual savings minus operating costs to investment on process control was about 60%.

This article relates to a period when process control implementation in mineral processing was far from obvious. It shows the "historical" process of discussion and taking decisions which several years later proved to be correct.

1.5/1.2 J. Tanila, U. Paakkinen, T. Huhtelin

Computer Control Pays Off at Finnish Copper Flotation Mill.

Engineering and Mining Journal, April 1973.

This article shows the development of process control at the Pyhasalmi concentrator from the late sixties till 1973.

The Pyhasalmi concentrator is described including the measurement and control system of particular sections like grinding, flotation, dewatering and drying. Stabilizing computer control is described where the computer controls the process variable to the set point determined by the control room operator. All control loops have been arranged mechanically so that the lower level is independent of the function of the upper level. Normal PI-and PID-algorithms dominate. Optimizing control determination of the set points is based for the copper flotation circuit on the criterion of economic recovery.

1.4 P.M. Fredericks, A. Tattersall, R. Donaldson

Near-Infrared Reflectance Analysis of Iron Ores.
Applied Spectroscopy Vol. 41, No. 6, 1987.

Near-infrared reflectance analysis (NIRA) has been applied to the rapid characterization of mineral samples. A suite of 82 West Australian iron ores was used to carry out the work. Approximately half the samples, chosen randomly, were used as a calibration set, while the remaining samples formed a prediction test set. Correlations were sought for eight of the significant practical properties of the samples. These properties were major element analysis, combined water, relative density and geothite concentration. Reasonably close correlations were obtained for most of the properties, except silicon, although the estimated prediction errors were worse than those obtained with conventional methods. Nevertheless, the speed and simplicity of the NIRA method should make it of use in many quality-control applications. The relatively poor result for silicon is probably due to the transparency of quartz in the near-infrared region.

1.4 S. Unsitalo, E. Makinin, D.O. Riska

On-line Neutron-capture Gamma Analysis of Ore Concentrates.

Inst. Phys. Conf. Ser. No. 62, 1982, Chapter 4.

A compact neutron gamma ray analyzer for on-line elemental analysis of ore concentrates has been developed and tested. The apparatus contains a 20 µg Cf-252 neutron source with a heavy water moderator and a large Ge(Li) detector protected from thermal and fast neutrons. The apparatus is suitable for quantitative analysis of the Co, Cu, Fe, Ni, S, Si and Zn content in bulk ore concentrates without sampling. This short article describes the instrument and gives data about accuracy achieved.

1.4 Tsahi Gorani

Physics of Recent Applications of PGNAA (Prompt Gamma-ray Neutron Activated Analysis) of Bulk Minerals.

American Institute of Physics Conference Proceedings. 1985 (Sci. Appl. Int. Corp., Sunnyvale, Ca, USA, 94089US).

The article describes the successful introduction into the industry on-line analysers under the name "Nucoalyser". It discusses physical principles and practical applications of "CONAC" analysers Model 300 (Laboratory), Model 500 (Slurry), Model 400 (Rapid, Belt), Model 200 (Chute/Batch) and the most developed, large, belt-type Model 100.

1.4 H.H. Vleizen, J. Van Brakel

On-Line Measurement Techniques in Coal-Handling Systems.

Powder Technology, 40 (1984).

This review paper is basically an introduction to the bibliography placed at the end, which lists about 187 items, dating from 1978 to 1984. They concern the on-line determination of the solids weight fraction and mass flow rate of coal in mechanical, hydraulic, or pneumatic transport, its particle size distribution, and its chemical composition, in particular the moisture, ash and sulphur content. It is an inventory of techniques commercially available, being tested, or under development, in the early eighties.

1.4 K. Leschanski

On-Line Analysis, Its Potential and Its Problems.

Part, Charact. I(1984); Verlag Chemie GmbH D-6940 Weinheim

In the application and the development of on-line methods for particle size analysis one has to distinguish three principally different problem areas:

a) allocation and preparation of a representative sample,
b) analysis of the sample,
c) evaluation of the results.

Methods and problems connected with these areas are discussed in this paper. Some of the methods available for rapid response analysis of particle size distributions mark the beginning of a new era of particle size analysis. One has to recognize however that a uniform solution of the problems of on-line particle size analysis is extremely difficult if not impossible to find. The boundary conditions vary to such an extent that similar methods or combinations of methods can rarely be used in different cases. Since instrument manufacturers will, in most cases, not be able to adapt their instruments to different industrial applications, specialists will have to solve the problem.

The author discusses and compares the following measuring principles for rapid response analysis: scattering of light, absorption of light, changes of electrical resistance, image analysis, ultrasonics, fluid flow techniques, pressure drop in accelerated flow, diffraction of light.

1.4 B. Holynska, M. Lankosz, J. Ostachowicz, K. Wolski

On-stream XRF Measuring System for Ore Slurry Analysis and Particle-size Control.

Int. J. Appl. Radiat Isot. Vol. 36 No. 5, 1985.

The originality of this article is that it describes a radio-isotope X-ray fluorescence measuring system developed not only for on-stream determination of major elements in a mineral slurry but also for continuous particle-size control. The system consists of several immersion gauges, particle size analyser, electronic unit and computer for data processing. The system has been used for simultaneous determination of Fe, Zn, Pb in flotation streams with accuracy within 3-15% [relative standard deviation 1 (1 RSD)] depending on metal concentration. Accuracy of the determination of weight percentage of ore particles smaller than 75 μm amounted to 5% (1 RSD).

Section 2 Iron Ore Concentrators and Pelletizing Plants

2. W.J. Nosek

Silica Control at Reserve Mining Company SME-AIME Annual Meeting, Atlanta Ga., March 1983.

The paper outlines the implementation of neutron activation on-line analysis and associated computer control loops for measuring and controlling the silica content of an iron ore concentrate. Modifications to the process introduced in 1980 enabled Reserve to reduce and control its final iron ore pellet silica content from 9.0±0.77 per cent to 5.0±0.26 per cent. Reserve taconite ore's main iron mineral is magnetite.

There have installed four neutron on-line analysers (NOLA). The four time-shared assay systems each analyse 12 slurry samples per hour. The final concentrate from each section is automatically sampled and analysed once every 20 to 30 minutes. The controller activates and processes ore silica analysis for a concentrating section within a five minute period. The principle of NOLA is briefly given. Reserve Mining Company's taconite beneficiation plant is located at Silver Bay, Minnesota.

2./1.3 D.L. Dingeman, M.W. Buckley

Process Modifications at Reserve Mining Company.
53rd Meeting of the Minnesota Section AIME Duluth, Minnesota,
Jan. 1980.

A computer based distributed control system with centralized monitoring and operator control is described. The system consists of four interconnected subsystems handling different functions. The structure of all subsystems is described in detail but no equipment characteristics are given. The description does not explain how particular subsystems influence the technology. It contains more information useful to automation experts than to technologists.

2/1.3 A. Hewitson, V. Balakrishnan

Computer Process Control for the Kudremukh Iron Ore Company Limited.

CIM Bulletin, Oct. 1984 Vol. 77 No. 870

A computer-based distributed process control system was implemented for all operations. The control system is examined from various stand points beginning with a description of its architecture, method of process input/output connection, and major hardware items. Software considerations and process applications are looked at. A discussion is presented on design considerations and design factors involved in the implementation of such a system. The type of process and the remote nature of the installation site are considered.

The purpose of the computer control system is to start, run and monitor plant equipment, provide automatic interlocking, control levels, flows, densities, etc. to give optimum rates and product quality. There should be full operator feedback, automatic report generation and maximum availability of the system. Hierarchicaldistributed architecture was used therefore. The central computer normally handles all control functions. When this computer fails a second level of distributed control takes over automatically by means of programmable controllers and analog controllers.

The normal information/control interface is through two CRT consoles connected to the central computers. In the event of computer failure the back-up system takes over by means of 3 "Videospec" stations acting as an interface between the system and the operator. Required operator intervention is greater but all important controls and interlocks are maintained.

2. G. Bourque, D. Runnels

Total Plant Control by a Process Computer at Québec Cartier's Mount Wright Property.

CIM Bulletin April 1977.

The entire operation, i.e., crushing, conveying, storing, grinding and concentrating is monitored and controlled through the process computer, by one operation via a CRT console. In case of computer failure, the control is automatically, and without process interruption, transferred to manual back-up panels. The process computer collects and automatically prints out shifts, daily and monthly reports on tonnage, metallurgy and equipment operating time. At present the system described (in 1977) is out of date from many points of view. It shows the approach to automation at the time central process computer use was an innovation in the mining industry. The computer was controlling 200 digital inputs (on-off switches) and 100 loops. A part of input/output to the computer was done by means of punched cards.

2. M. Cross, R.W. Young, P.E. Wellstead, R.D. Gibson

The Mathematical Modelling and Control Aspects of the Pelletizing of Iron Ores.

Agglomeration 77, 403-424, Chapter-22, 1977.

Described is a comprehensive research program devised to evaluate process parameters and to provide the information required to optimize operations of the British Steel Corp. first pelletizing plant. This program included effort for the development of mathematical models of the various constituent processes involved in pelletizing.

A mathematical model of the balling drum circuit has been developed which not only describes how its behaviour varies under different operating conditions, but also demonstrates its response to changes in these conditions. The model is explained, shown on diagrams but not presented in mathematical equations what makes this article much less useful. Another model of induration is discussed as well. A bibliography on pelletization and modeling consisting of 26 items is given.

2. P.E. Wellstead, N. Munro, M. Cross

Modeling and Control of the Balling Drum Circuit of an Iron Ore Pelletizing Plant.

IFAC Symposium, Automation in Mining, Mineral and Metal Processing, Johannesburg, Sept. 1976.

A mathematical model of "surging" phenomenon in balling drum is developed. "Surging" or periodic fluctuation in the number of pellets produced can be avoided by inserting a pellet hold-up device in the recirculating path of undersize pellets. When the hold up is sufficiently large the frequency response will be so attenuated at high frequencies that surging is quelled. The digital simulation of the pellet balling developed by one of the authors is mentionned and used for testing the proposed method of attenuation of oscilating phenomenon called "surging". References presented give a possibility of reviewing the theory of pelletizing as it was developed up to 1975.

Section 3 Particular Circuits

3.1 Interlock system
3.2 Grinding circuit
3.3 Fluidized bed
3.4 Leaching
3.5 Coal
3.6 Ph-control
3.7 Silica control
3.8 Flotation
3.9 Blending
3.10 Particle size

3.2 J.L. Vanderbeek, J.A. Herbst, L.B. Hales, R.J. Pennington

An Investigation of the Effects of Mill Volumetric Load Level, Percent Solids, and Speed Upon Semi-autogenous Mill Operation.

The SAG milling of ores with markedly variable grinding rates presents definite process control challenges. Decisions must be made regarding the selection of the most appropriate combination of mill volumetric load level, percent solids and mill speed for the combination of ore types being processed at the moment. An investigation was performed concerning the effects of these parameters. General results are presented. These results are crucial for a design of an enhanced SAG mill control procedures.

3.2 J.A. Herbst, Y.C. Lo, J.E. Bohrer

Increasing the Capacity of a Phosphate Grinding Circuit with the Aid of Computer Simulation.

Report of Utah Comminution Center, U. of Utah, Salt Lake City Control International, Inc., Salt Lake City, New Wales Operation, International Minerals and Chemicals Corp. Mulberry, 1987.

"Population Balance Models" have been developed for the plant ball mill and classifier system. Verification of the model was based on series of batch tests and two plant test campaigns. The model permitted to investigate and predict the effects of feed rate, per cent solids, ball size and mill material filling, etc. on grinding. Understanding the effects of operating variables on breakage kinetics and the interplay between kinetic, transport and classification has contributed significantly to increasing the mill capacity. Eleven references dating from 1971 to 1986 are cited.

3.8 J.A. Frew

The Use of Computers in Zinc Flotation Control.

Computers in Mining - 1983, The Australian Institute of Mining and Metallurgy.

The introduction of on-stream analysis in flotation circuits has raised the possibility of automatic control of flotation performance by digital computers. The development of control strategies is discussed. The particular control schemes investigated have included control of activator and collector addition variable, circuit configuration or concentrate destination and water addition in this described concentrator.

The most difficult type of disturbance to handle by process control is change in ore type (ratios of particular minerals).

The schemes on which are based algorythms are purely empirical; therefore they need careful and frequent adjustments.

3.2 G.A. Duckworth, A.J. Lynch

The Effect of Some Operating Variables on Autogenous Grinding Circuits and Their Implication for Control.

CIM XIV International Mineral Processing Congress, Oct. 1982.

Three variable are considered as most important to circuit operation: mill fresh feed size distribution, mill load level and mill content percent solids.

Small changes in feed size distribution can be compensated for by the appropriate adjustment of fresh feed rate (and hence mill load level) and water addition rates provided that a continuous measure of mill feed size distribution is available.

The article gives a very good explanation of principles on which conventional or autogenous grinding circuits are controlled. It refers to the continuous measurements of coarse ore size distributions on conveyor belts as described by E. Gallagher, ("Optoelectronic Coarse Particle Size Analysers for Industrial Measurement and Control" PhD. Thesis, University of Queensland, 1976) and installed in several industrial grinding circuits (for example Foxboro PSD sizers at Peko-Wallsend Ltd. at Warrego, Australia and at AMAX Henderson in Colorado, U.S.A.). Mathematical modelling of an autogenous and a semi-autogenous mill is described.

3.2 M.H. Moys, A. Montini

The Use of Conductivity Measurements (Obtained from a Probe Mounted in the Mill Shell) in the Control of Grinding Mill.

CIM 88 Annual General Meeting of CIM-1986.

Authors claim that information relating to the slurry near the feed end of the mill provided by conductivity probes, enable designing controllers which can effectivity control the rheology of the pulp. This should result in more stable and hence more efficient mill operation. Tests supporting this thesis have been carried out in a pilot plant made available by the South Africa Council for Mineral Technology (MINTEK).

The proposed control is based on feed-forward as opposite to mostly used feed-back which permits reacting after a certain laps of time.

3.2 R.E. Hathaway

Selection and Sizing of Instrumentation and Control Systems. Size Controlled Grinding Circuits.

Design and Installation of Comminution Circuits, editors A.L. Mular, G.V. Jergensen II, Society of Mining Engineers, New York 1982.

The author is a representative of ARMCO Autometrics (Boulder, Colorado 80301) which designs and implements automatic grinding circuit control systems called Armco Grinding Systems (AGS). In this article only particle size based grinding control is discussed. Each control system must be tailored to the needs of the individual circuit. The Automation by ARMCO is based on line product size analyses by Autometrics Particle Size Monitor (PSMO). As the result of AGS implementation increases in production and/or net revenue from 3 to 10% have been reported.

As a minimum the following instrumentation must be installed before the circuit analysis, for process control system design, begin.

New ore feed belt scale
Sump level indicator
Cyclone feed density
Water flow meter
Slurry flow meter
Pump horsepower indicator
Particle size monitor
Strip chart recorders
Mill horsepower indicator

Steps to be taken to properly design a process control system are briefly described. This is a very useful article.

3.2 D.G. Hulbert

Multivariable Control and Optimization of the Operation of a Milling Circuit at East Driefontein Gold Mine.

MINTEK Report M98, S.A. Randburg, May 1983.

The report describes a successful application of a multivariable controller to an industrial milling circuit. Set points for the controller are the particle size of the product, and the flowrate and density of the slurry fed to the primary cyclones.

Mathematical models for grinding and hydrocyclones were used in a programme for the dynamic simulation of a grinding circuit. A linear dynamic model relating three important output variables of the plant and three control actions has been derived.

The author thinks that multivariable control system without a procedure for automatic optimization is better because it avoids difficulties resulting from shutdowns, partial shutdown, instrument faults, etc. Such disturbing circumstances would adversely affect the calculations for optimization.

3.2 R.E.J. Putman

Self-Tuning Regulators for Control of Comminution Circuits.

Design and Installation of Comminution Circuits, editors A.L. Mular, G.V. Jergensen II, Society of Mining Engineers, New York 1982.

This article compares novel self tuning regulators, their theory and application, with older type and widely used controllers. Algorithms used here are distinctly different and include automatic adjustment features which permit them to adapt to unmeasured changes (for example in ore grindability) or process non-linearities (as exhibited by hydrocyclones). These regulators are particularly useful for distributed control systems.

3.2 O.G. Pauw, R.P. King, K.C. Garner, P.C. Van Aswegen

The Control of Pebble Mills at Buffelsfontein Gold Mine by Use of a Multivariable Peak-Seeking Controller.

Journal of the South African Institute of Mining and Metallurgy, March 1985.

This paper describes the most significant relationships among the operating and control variables in the plant. Experimental data from the plant are exhibited, peak-seeking control algorythms and controller development described.

Pebble feed and water addition were used as control variables while the measurement of mill power was the only measurement input on both controllers. The pebble mill controllers described were developed as an integral part of a comprehensive grinding-circuit control system. The strategy consisted in maximization of the production of fines at constant fineness of grind. The first known application of multivariable peak-seeking controllers on an operating plant.

1.3 3.2 3.8 P.J. Lean

Computer Control of Grinding and Flotation at the Zinc Corporation, Ltd., and New Broken Hill Consolidated Ltd.

Mill Operators Conference 1978, North West Queensland Branch.

This paper describes process control systems which have been in use since 1974-75 to 1978, and benefits these system gave to processing plants.

3.6 R. Biss, L. Duval

pH Control Plant Practice Performance at Niobec Mine Quebec.

XIV International Mineral Processing Congress, Toronto, Oct. 1982.

The article describes the application and use of a simple analog meter and controller in a niobium minerals flotation plant. pH control is of prime importance for good results of a plant where three sections of flotation (carbonate, pyrochlore, pyrite) are in operation.

3.1 J.V. Becker

Designing Safe Interlock Systems.

Chemical Energy, Deshboch, Oct. 1979.

The article gives elementary review of safety interlock systems, presents sample interlock logic diagrams and gives examples of a number of typical systems. Summary of required technical approaches to any interlock system design is presented.

3.2 P. Uronen, M. Tarvainen, H. Aurasma

Audiometric Control System of Wet Semiautogenous and Autogenous Mills.

Automation in Mining Mineral and Metal Processing Second IFAC Symposium, Proceedings, Johannesburg, 1976.

The audiometric control system has been developed at the concentrator of Outokumpu Oy, Vuonos nickel ore mine. In the automatic computer control system the controlled variable is the noise and the manipulated are the components of the feed, namely the water to feed ratio, fine ore and lump feeds. Controlled is also the power to the mill.

The primary aim of the work was to decrease blockages of the mill and to maximize the total feed of the ore. The algorithm used was a normal PI-algorithm tuned to work in changing process conditions. With the help of this system mill overloadings and water disturbances could be reduced.

3.4 B. Gaudernack, O.B. Michelsen

Control of a Solvent Extraction Process for Rare Earth Separation by Means of a Computer-Based On-Stream XRF Analytical System.

International Solvent Extraction Conference ISEC 77, CIM Special Volume 21, 1979.

The paper deals with the application of on-stream analysis to the monitoring and control of a commercial solvent extraction plant for the production of high-purity yttrium oxide, at Kjeller, Norway. Radioisotope X-ray fluorescence principles were used to introduce automatic continuous analytical surveillance. "MINTEK" instruments sold by G.E.C. Elliot Process Instruments Ltd., Lewisham, London, G.B., were used. Instruments and radiations sources are described and basic principles of calculation presented, waiting time for necessary and important process information is being reduced and cost involved in obtaining such information cut down. The next step of development assay may be a fully automatic control of the flow rate.

3.8 K.C. Rabson, P.E. Carroll

Development of an Automatic Reagent Feeding System for the Strathcona Mill.

CIM Bulletin, Feb. 1975.

The reagent feeding system was developed to meet the requirement of a central control room receiving X-ray on-stream analysis from 15 pulp streams. Accurate reagent solutions are obtained by mixing measured amounts of concentrated reagend and water. These solutions are fed through flow meters to reagent distributors which feed the circuit at approximately 120 addition points. Controllers in the control room position valves to give the desired flow rates. Current (1975) efforts are directed toward complete computer control of all reagent additions in the plant.

3.5 R.S.C. Rogers, H. Bezorgmanesh, T. Gozani, T. Brown

Continuous On-Line Nuclear Analyser of Coal.

1980 American Mining Congress International Coal Show, Chicago, May (1980).

CONAC (Continuous On-Line Nuclear Analyser of Coal) instrument development and its use to elemental composition moisture content and BTU measurements are described.

The nuclear analyser employs prompt neutron activation analysis (PNAA) to provide the elemental analysis of the coal. Typically analysed elements will include H,C,S,N,Cl,Si,Al,Fe,Ca,Na and Ti. Results are available within minutes of the beginning of a data acquisition period. PNAA measures elemental quantities within a coal without regard for the molecular bondings of the elements.

3.9 C.G. Schofield

Homogenization/Blending Systems Design and Control for Mineral Processing (with Fortran Programs).

Trans Tech Publications, 313 p. 1980.

This book includes the following chapters:

1. Basic Concepts of Raw Material Preparation and Homogenization
2. State of the Art of Homogenization System Design
3. Review of Stockpile Raw Material Stocking and Reclamation Methods
4. Simulation of the Linear Stockpile Pre-Homogenizer
5. Optimal Stockpile Pre-Homogenizer Design in the Face of Random Materials Input Quality Variation
6. The Circular Stockpile Pre-Homogenizer
7. Mixing in a Closed Circuit Ball Mill System
8. Computer Based Steady-State Proportioning for Cement Raw Materials Variability Control
9. Fluidized Homogenizers, Silos, Hoppers and Transportation Devices
10. Quarry Blending: The Application of Select Quarrying Procedures
11. Forecasting and Feedforward Control in Minerals Processing
12. Simulation and Control of the Overall Pre-Kiln Raw Material Preparation Systems
13. Conclusions, Overview and Collection of Important Design Considerations
14. References

1.4/3.10/3.2 R.E. Hathaway, D.L. Guthals

The Continuous Measurement of Particle Size in Fine Slurry Processes.

CIM Bulletin, Feb. 1976.

The article describes a prototype test program at the US Steel's Minntac Plant and calibration of the first four production Autometrics PSM-200's in four different concentrators. When the article was written more than 40 concentrators in Canada, the US, Africa and the Philippines had installed the Autometrics PSM System 100. The "second generation" System-200 is capable of measuring finer grinds and of accurately measuring magnetized slurries of iron ores. Both PSM Systems transmit two beams of ultrasonic energy across a slurry sample. The frequency of a beam is chosen so that its attenuation is highly sensitive to changes in particle size. The second beam is barely a little affected by particle size. Both beams are affected by the slurry density. An electronic comparison of outputs of two sensors yields two separate signals - particle size and per cent solids. The magnetic agglomeration of fine particles of iron ore tends to "fool" the instrument to read coarser distribution than actually exists. For demagnetization 400Hz, 800-oersted coil was used. The following plants were using PMS System-200:

1. US Steel's Minntac Plant, Near Mountain Iron, Minnesota
2. Tilden Mining Company's Concentrator Near Ishpeming, Michigan
3. Craigmont Mine's Magnetite Recovery Plant
4. Brunswick Mining Concentrator Near Bathurst, New Brunswick